The Impact of Galaxy Formation on the X-ray Evolution of Clusters

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ABSTRACT
We present a new model for the X-ray properties of the intracluster medium that explicitly includes heating of the gas by the energy released during the formation of cluster galaxies. We calculate the evolution of clusters by combining the semi-analytic model of galaxy formation of Cole et al. with a simple model for the thermodynamic properties of the intracluster medium. We focus on the cluster X-ray luminosity function and on the relation between X-ray temperature and luminosity (the T-L relation). These properties are known to disagree with predictions of simpler cluster models based on scaling relations which neglect gas cooling and heating processes. We show that cooling alone is not enough to account for the flatness of the observed T-L relation or for the lack of strong redshift evolution in the observed X-ray luminosity function. Gas heating, on the other hand, can solve these two problems: in the ΛCDM cosmology, our model reproduces fairly well the T-L relation and the X-ray luminosity function and, furthermore, predicts only weak evolution in these two properties out to $z = 0.5$, in agreement with recent observational data. A successful model requires an energy input of 1–2 $h^{-1/2}\,10^{49}$ ergs per solar mass of stars formed. This is comparable to the total energy released by the supernovae associated with the formation of the cluster galaxies. Our model therefore requires a (perhaps unrealistically) high efficiency for the absorption of supernovae energy by the intracluster gas, or additional sources of energy, such as mechanical energy from AGN winds. The amplification of an initial energy input by the response of the intracluster medium to protocluster mergers might ease the energy requirements. Our model can be readily tested by observations of X-ray cluster properties at redshift one and greater with the Chandra and Newton observatories.

Key words: galaxies: formation

1 INTRODUCTION

One of the fundamental puzzles of the X-ray universe concerns the relation between the X-ray luminosity and gas temperature of clusters. A simple scaling analysis (Kaiser 1986) suggests that the temperature and luminosity should be related by $T \propto L^{1/2}$. Temperatures have now been measured for the diffuse X-ray emission for an extensive range of groups and clusters (David et al. 1993; Ponman et al. 1996; Allen & Fabian 1998; Markevitch 1998; Mulchaey & Zabludoff 1998; Arnaud & Evrard 1999; Helsdon & Ponman 2000). In contrast to the slope of the theoretical relation, the observations show a much shallower trend, approximately $T \propto L^{1/3}$.

A closely related problem is the evolution of the cluster X-ray luminosity function. Kaiser's (1986) analysis of the evolution of the X-ray properties of clusters suggested that dense, X-ray luminous associations of galaxies would be common in the intermediate and high redshift universe. This possibility was soon ruled out by the initial results of the EMSS cluster survey (Gioia et al. 1990; Henry et al. 1992), which quickly established that clusters in the distant universe have comparable luminosity to those of the local universe. This has been confirmed in more recent ROSAT surveys.

Initially, one might hope that the physics of gas cooling (omitted from Kaiser's analysis) might resolve this discrepancy. Unfortunately, it is extremely difficult to include cooling into numerical simulations in a way that is stable. The difficulty is inherent to the problem. Because the universe is dense at early times, cooling becomes very efficient. This leads to an unrealistically large fraction of the halo baryon content cooling to the temperature of the smallest resolved galaxies. As White & Rees (1978), White & Frenk (1991), Cole (1991), Suginohara & Ostriker (1998) and Pearce et al. (2000) amongst others have shown, some form of heating is required to overcome this catastrophe. In addition, as we show in Appendix A, cooling is relatively more important in lower mass objects. This tends to make these systems more compact and over luminous relative to the scaling-law prediction. Alternatively, if we examine how the cooled gas fraction depends on cluster mass (Appendix A), it becomes clear that the cooled fraction depends too weakly on cluster temperature to account for the discrepancy. Cooling cannot (by itself) solve the temperature-luminosity relation problem.

One approach that has given encouraging results is to assume that the gas is "preheated" before collapsing into the cluster (Evrard & Henry 1991; Kaiser 1991; Navarro, Frenk & White 1995). This creates an entropy floor in the gas ensuring that it remains diffuse in low mass systems and results in a much improved match to the T-L relation (Balogh, Babul & Patton 1999; Valageas & Silk 1999; Tozzi & Norman 2000). This model also provides an encouraging match to the surface brightness profile of low mass groups (Ponman et al. 1999). The problem lies in explaining the origin of this diffuse heating and its apparent uniformity.

Prolonged heat input from galaxy formation has been suggested as a solution by Wu et al. (1998, 1999a) and Cavaliere et al. (2000). They adopted the approach of accounting for the energy input from supernova explosions by measuring the change in the energy of a test gas configuration relative to the case where there is no heat input. The three sources of energy, gravity, cooling and supernovae, can then be treated separately to define a new gas distribution. This approach successfully accounts for the shallow present-day temperature-luminosity (T-L) relation if galaxy formation has a roughly uniform efficiency in haloes of different mass. Since the binding energy per particle increases with halo mass, while the additional heating remains roughly constant, high mass clusters are almost unaffected while the gas in low mass groups becomes unbound.

In this paper, we develop a model in which the semi-analytic galaxy formation scheme of Cole et al. (2000) (GALFORM) is used to follow the evolution of the supernova heating rate and hence the evolution of the gas content of dark matter haloes. The scheme is an elaboration of the methods described by Baugh et al. (1998), and uses similar principles to the models described by Kauffmann, White & Guiderdoni (1993) and reviewed by Somerville & Primack (1999). We apply the model to study the evolution of the X-ray luminosity function and the temperature-luminosity relation.

The structure of this paper is as follows. Our method for coupling the supernova energy injection to the gas distribution in the halo is presented in §2. The predicted X-ray properties are detailed in §3. In section §3.1, we show that supernova heating is able to produce the observed slope and normalisation of the present-day T-L relation only if the efficiency with which the supernova ejecta couple to the diffuse intracluster medium (ICM) is very high. This requires, for example, a tilted stellar initial mass function (IMF) with an overabundance of high-mass stars, or a contribution from AGN activity to the energy balance. In §3.2, we apply this model to the X-ray luminosity function. We compare the evolution predicted by the model within a flat $\Omega_0 = 0.3$ CDM cosmology with the available observations of intermediate redshift clusters. In §3.3, we consider the X-ray properties of the universe at very high redshifts, and in §3.4, we compare the expectations based on the galaxy formation model with two extreme models for the redshift evolution of the heat input. Further discussion of the problems and a restatement of our conclusions are given in §4 and §5.

2 THE MODEL

Wu et al. (1998, 1999a) have suggested a simple approach that allows non-gravitational heating to be incorporated into the calculation of cluster properties. Starting from a default distribution, the gas is redistributed to larger and larger radii until the total energy increase matches the energy input from galaxy formation. The effect of heat input may affect the distribution of gas within clusters in a variety of ways. Our approach differs from Wu et al. in the way we determine the default gas distribution, and in the way we adapt the gas distribution to the excess energy input. While Wu et al. adopt a default gas distribution based on the clusters' gravitational binding energy, our default profile is explicitly based on the observed properties of high temperature rich clusters. We are able to do this because the ranges of excess energy that we consider have little impact on the gas distribution in these systems. Our method of normalising implicitly includes the effect of gas cooling as we describe below. Similarly, our approaches differ in the way in which the excess energy is included. Wu et al. explore a variety of heating models in which heating occurs either by heating the gas isothermally, or by varying the polytropic index. In contrast, our approach is empirical and motivated by the observations of Arnaud & Evrard (1999) and Lloyd-Davies, Ponman & Cannon (2000) who find that the gas profiles of clusters become systematically shallower at lower temperatures. We therefore assume that the overriding effect of heating is to reduce the slope of the radial density profile of the gas. Our empirical approach does not require us to choose explicitly between the isothermal and polytropic regimes. Instead, for our given density profile, we solve for hydrostatic equilibrium in order to determine the gas temperature.

The dark matter density of the halo follows a Navarro, Frenk & White (1997, NFW) profile as described by Cole et al. (2000). We parameterise the gas distribution using a conventional β model (Cavaliere & Fusco-Femiano 1976). The first step is to calculate the default radial profile. We initially distribute the gas with a core radius that is a fixed fraction (7%) of the virial radius and set $\beta = 0.7$ in order to match observations of the most massive clusters (eg. Lloyd-Davies, Ponman & Cannon 2000). The temperature of the gas at the virial radius is set to $0.5T_{\rm vir}$ as suggested by the numerical simulations of Eke, Navarro & Frenk (1998) and Frenk et al. (2000). The temperature of the gas at smaller radii is then found by solving for hydrostatic equilibrium in the gravitational potential of the dark matter. This technique accurately reproduces the luminosity weighted temperature of the cluster simulated by Frenk et al. (2000). We adjust the normalisation of the default gas profile so that the baryonic mass (ie. gas plus galaxies) enclosed within the virial radius is equal to the cosmic baryon fraction. Treating the total mass in this way takes into account the effect of

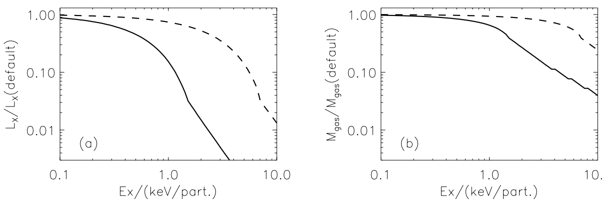

Figure 1. Panel (a): the dependence of the X-ray luminosity of a cluster on the excess energy injected into the ICM. The luminosity is plotted relative to the luminosity of the default profile. The two clusters shown have virial temperatures of 1 keV (solid line) and 5 keV (dashed line). The kink at $L_X/L_X(\mathrm{default}) \sim 0.03$ corresponds to the minimum allowed β-slope of 0.2. Larger excess energies are accommodated by increasing the temperature of material at $R_{\rm vir}$. The fraction of the default gas mass remaining within the cluster virial radius is shown in Panel (b).

cooled gas that is locked into galaxies, thus reducing the hot gas fraction of the cluster. X-ray luminosities are calculated from the gas within the cluster virial radius since material at larger radii is unlikely to be in hydrostatic equilibrium. In practice, this cut-off has little influence on the X-ray luminosity since this is dominated by the densest material in the cluster core. We exclude gas within the cooling radius when calculating the luminosity-weighted temperature since this material is likely to have multi-phase structure that is not represented by our model.

Having established the default profile for a given cluster, we reduce the slope of the gas profile until the total energy (i.e., thermal plus gravitational energies) of the gas is increased by the required amount. As the profile changes, we keep the pressure (and thus density) at the cluster virial radius fixed at the value found for the default profile. Our scheme does not conserve the mass of gas within the virial radius. Gas that is ejected is displaced to the virial radius and included in the energy balance calculation, but not in the calculation of the X-ray luminosity. The temperature of this material is assumed to be the same as that of the gas at $R_{\rm vir}$. This corresponds to the lowest plausible temperature for the expelled gas to be both in pressure equilibrium with its surroundings and buoyant with respect to the remaining cluster material. We have chosen the virial radius as the point at which to normalise our density profiles because this approximately delineates the region of the cluster that is in virial equilibrium and separates it from the outer parts of the cluster that are dominated by bulk inflow. Outside the virial radius, the gas is unlikely to be in hydrostatic equilibrium. Close to the virial radius, the infall gas is shocked so that its bulk motion is converted to internal energy. In three dimensional simulations, the shock radius is more poorly defined because the infalling material already has a range of initial entropies and thus tends to smooth out the shock. In the 1-dimensional simulations of Ponman & Knight (1997), where the infalling material has uniform initial entropy, the shock radius occurs at 1-1.5$R_{\rm vir}$, in line with the boundary radius we assume here.

Figure 1 shows the relation between energy input (ie. the excess energy), $E_{\rm x}$, and X-ray luminosity for clusters with virial temperatures of 1 and 5 keV (Panel (a)), and the fraction of the original gas mass that remains within the cluster virial radius (Panel (b)). Note that the decline in X-ray luminosity is much more rapid that the decline in the gas mass within $R_{\rm vir}$. Experimenting with different schemes for modelling the effects of heating, such as keeping the mass within $R_{\rm vir}$ constant, shows that the fixed pressure assumption is the most effective at reducing the X-ray luminosity for a given energy input. As can be seen from the figure, there is a limit to the overall energy increase that can be accommodated by flattening the gas profile. If the required profile slope is less than 0.2, we fix β at this value and instead allow the temperature of the gas at the virial radius to rise. Since the pressure at this radius is kept fixed, the gas density must then fall and a greater fraction of the gas mass is ejected. The choice of the minimum β value is not critical since the total energy of the cluster depends only very weakly on β for $\beta < 0.4$. The lowest values in observed systems are $\beta \sim 0.35$ (Lloyd-Davies, Ponman & Cannon 2000).

Note that even though the calculation does not take cooling into account explicitly, radiative energy loss is implicitly included because of the way in which we normalise the simulations to the observed properties of the brightest clusters as described below. In the absence of supernova heating, the fraction of the gas mass contained within the cooling radius shows little mass dependence (Appendix A). Thus, cooling has a similar effect in both the high temperature and low temperature clusters and (on its own) does not tend to flatten the slope of the T-L relation. We discuss the effect of combining supernova heating and radiative cooling in §4.

X-ray luminosities and luminosity-weighted temperatures for individual haloes are calculated using Peacock's (1996) analytic fit to the Raymond-Smith cooling function. This includes both bremsstrahlung and recombination processes and is adequate for the range of haloes considered here. Representative dark matter haloes are generated using a Monte-Carlo method based on the extended Press-Schechter model as described by Cole et al. (2000). This ensures that our model includes the correct halo mass distribution and assigns collapse redshifts to individual haloes. We use the properties of the halo at its collapse time for determining the X-ray properties. Gas temperatures are calculated using only material outside the cooling radius.

We adopt the cosmological parameters $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$, $\sigma_8 = 0.8$, $\Gamma = 0.19$, where Λ_0 is the cosmological constant measured in units of $3H_0^2/c^2$, σ_8 is the linear theory mass variance in spheres of radius $8h^{-1}$Mpc at the present and Γ is the shape parameter defined by Efstathiou, Bond & White (1992). With these parameters, our model temperature function matches the data of Eke et al. (1998). Note our values differ slightly from those inferred by Eke et al. because our luminosity-weighted gas temperatures are ~15% higher than the cluster virial temperatures they assume. This offset is consistent with the results of hydrodynamical simulations of clusters (eg. Frenk et al. 2000), and depends on the profile adopted for the gas distribution in the central region of the clusters (which dominates the X-ray luminosity). In order to match the observed temperature function, we have lowered σ_8 from 0.93 to 0.80. We retain the $\Gamma = 0.19$ power spectrum shape preferred by Eke et al.

We normalise the model to fit the observed temperatures and luminosities of the most luminous X-ray clusters by adjusting the cosmic baryon fraction. These clusters are almost unaffected by the energy injection. Since the observed cluster luminosities depend on H_0, the gas fraction required to normalise the model depends on $h^{-3/2}$. We find that $\Omega_b = 0.025h^{-3/2}$ gives a good fit to the observed X-ray luminosities of clusters with virial temperatures greater than 7 keV. Once the model is normalised in this way, the gas fractions within $1.5h^{-1}$ Mpc are consistent with observed values.

In order to trace the evolution of the energy injected by star-forming galaxies, we use the semi-analytic model of galaxy formation of Cole et al. (2000, GALFORM). This provides a tabulation of the stellar mass that has formed in each halo by its collapse epoch. The model correctly follows the build-up of the stellar content of dark matter haloes as a function of redshift and the variation in stellar content between haloes. The fraction of baryons remaining in the intracluster medium has a systematic variation with halo mass and a random scatter in haloes of a given mass due to different star formation histories. The fraction of energy produced by supernovae that couples with the ICM is left as a free parameter that we will adjust in order to fit the present-day form of the T-L relation. It should be noted that our aim here is not to produce a revised scenario for galaxy formation. This would require us to reconsider the star formation law and the complex interplay of galaxy formation physics in order to create a new model that matched the luminosity function, colour distributions, etc of observed galaxies. Instead, we limit ourselves to investigating the impact of galaxy formation using an ab-initio model that has already been shown to reproduce most observational data extremely well. The net effect of the heating of the intracluster medium is a reduction in the cooling rate. In order that the global stellar mass to light ratio remains unchanged, the effects of heating need to be compensated by an increase in the baryon fraction. Thus, introducing the additional physics of supernova/AGN heating into GALFORM tends to bring the baryon fraction (Cole et al. adopt $\Omega_{b,GF} = 0.012\,h^{-3/2}$ with $h = 0.7$) into line with that used in the X-ray calculation. In this paper, we assume that the cosmic star formation history predicted by GALFORM will be unchanged and investigate the sensitivity of the results to variations in the heating rate in §3.4. We discuss the limitations of this investigation, and how it can be improved in §4.

We treat the excess energy associated with the formation of each unit mass of stars as a free parameter. A single type II supernovae is expected to release an energy of 10^{51} ergs (eg. Woosley & Weaver, 1986). However, an unknown fraction of this energy may be radiated away before heating the ICM. For a Salpeter IMF (with an upper mass limit of $125\mathrm{M}_\odot$, lower mass limit of 0.1 $\mathrm{M}_\odot$ and a minimum mass for core-collapse of $8\mathrm{M}_\odot$), 0.007 supernovae are expected per Solar mass of stars formed (Iben & Renzini 1983; Madau et al. 1998). A higher rate applies if the IMF is skewed towards high mass stars, or if the lower mass limit for the progenitors of supernovae is reduced (Chiosi et al. 1992). Lower levels of energy input are suggested by recent analyses of the metal abundance of the intracluster medium (Renzini, 1997, Kravtov & Yepes, 2000). We adopt the parameterisation that an energy $\epsilon_{\rm SN} 10^{49}\,\mathrm{ergs\,s^{-1}}$ goes into heating the ICM per $\mathrm{M}_\odot$ of stars formed. We can convert this into an energy per baryon once the fraction of baryons converted into stars ($f_{\rm gal}$) is known. For our models, this is roughly $0.16h^{1/2}$. Thus the excess energy can be expressed as

$$0.50\epsilon_{\rm SN}\left(\frac{f_{\rm gal}}{0.16h^{1/2}}\right)h^{1/2}\mathrm{keV}\ \text{per particle}$$

Note that the numerical value of $\epsilon_{\rm SN}$ depends on the Hubble constant because the total baryon fraction required to give the correct cluster X-ray luminosities varies as $h^{-3/2}$ while the stellar mass depends on h^{-1}.

Since it seems likely that a significant fraction of a supernova's energy will be lost as radiation from the supernova remnant, and not be available as kinetic energy that can heat the surrounding gas, we should expect $\epsilon_{\rm SN}$ to be significantly less than unity (eg. Thornton et al. 1998). However, additional energy might be available from active galactic nuclei at the centres of clusters. This energy may be released by jets that transfer significant kinetic energy to the surrounding gas. Although the details of the fuelling of AGN activity are unclear (see Nulsen & Fabian 2000, for a recent discussion), the requirements for AGN activity are similar to those for star formation in disks and the two processes may be closely linked. We will assume that the AGN activity parallels the star formation activity in the galaxies. If all galaxies harbour black holes with masses close to those suggested by Magorrian et al. (1998), we can estimate the available energy as follows. The total energy radiated by each black hole of mass $M_{\rm BH}$ is approximately $0.1M_{\rm BH}c^2$. Magorrian's relation suggests $M_{\rm BH} \sim 0.06M_{\rm stars}$ where $M_{\rm stars}$ is the mass in stars (strictly, the bulge mass). Combining these relations shows that the available energy is $\sim 10^{52}$ ergs per $M_\odot$, or $\epsilon_{\rm SN} = 1000$. Thus, an energy contribution from AGN may easily exceed that from galaxies by several orders of magnitude. For this reason we will allow for the possibility that $\epsilon_{\rm SN} > 1$.

3 RESULTS

3.1 The Temperature-Luminosity Relation

As expected, if no excess energy is included in the calculation, the model clusters fail to match the observed slope of the T-L relation. Data from David et al. (1993) show a slope close to $T \propto L^{1/3}$, a result that has been confirmed by analysis of more recent ASCA observations (Arnaud & Evrard 1999). The brightest clusters may follow a shallower slope than this when the luminosities are corrected for contamination by the cooling flow (Markevitch 1998; Allen & Fabian 1998). The $L^{1/3}$ slope can be extrapolated to groups of much lower luminosity (Ponman et al. 1996; Mulchaey & Zabludoff 1998; Helsdon & Ponman 2000). The X-ray properties of our model clusters are compared with those data in Figure 2, in which the dashed line shows the median relation for the case when there is no excess energy. We prefer to plot this relation with temperature on the vertical axis as the observational uncertainties are far greater for X-ray temperatures than luminosities.

In order to match the observed form of the T-L relation, it is necessary to introduce very substantial heating. In the upper panel of Fig 2, we show the T-L relation at $z = 0$ in a model with a heating efficiency $\epsilon_{\rm SN} = 1.3h^{-1/2}$. This is greater than can be accounted for by supernova feedback alone showing that a significant contribution from AGN is

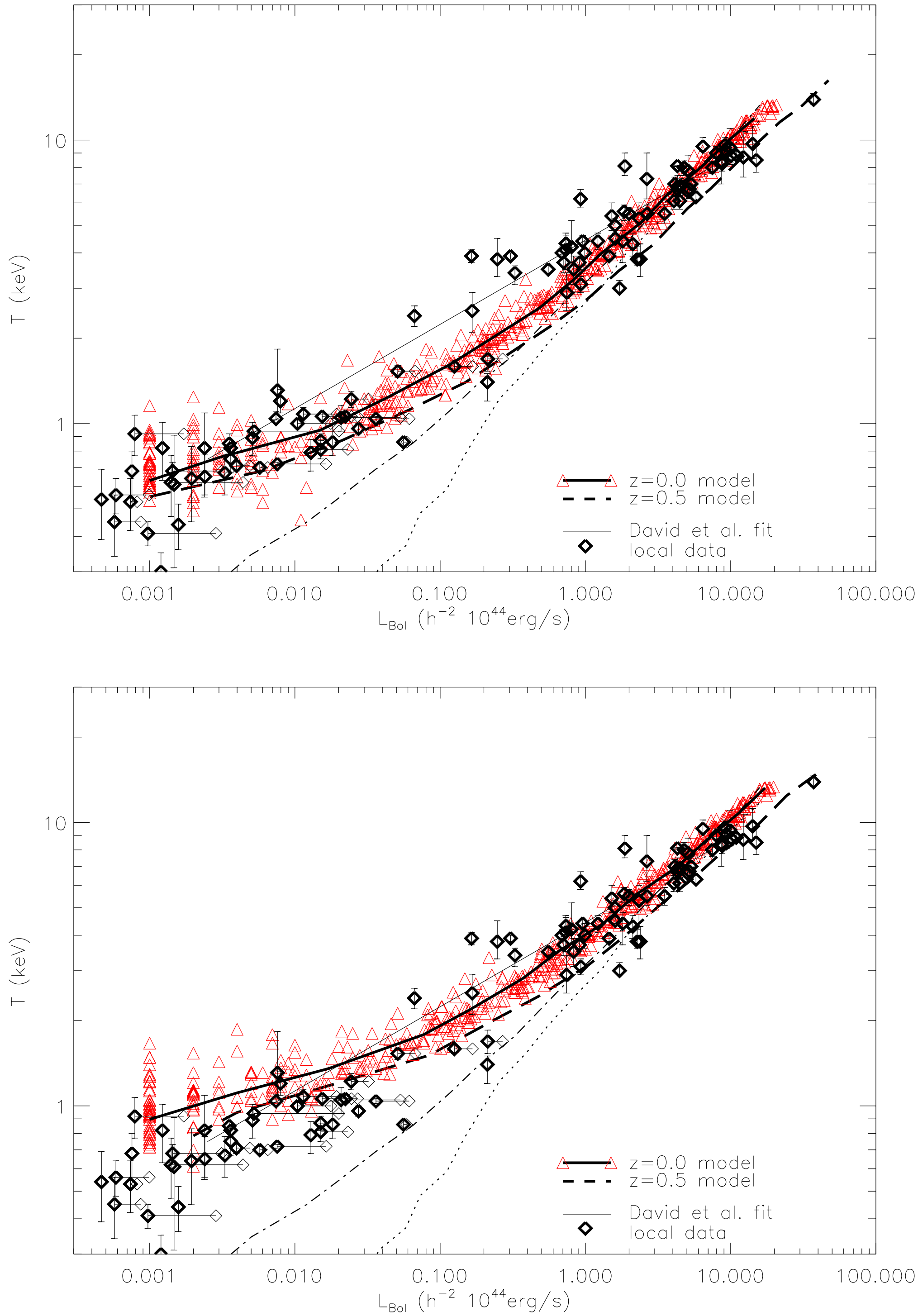

Figure 2. *Upper panel:* a comparison of the predicted and observed T-L relations for a heating efficiency $\epsilon_{\rm sn} = 1.3\,h^{-1/2}$. The distribution of model clusters at $z = 0$ is shown as open triangles, with the thick solid line illustrating the median T-L relation. The median T-L relation at $z = 0.5$ in this model is shown by the thick dashed line. Bold diamonds are data points for clusters and groups within $z < 0.1$ taken from a variety of sources as described in the text; lighter diamonds illustrate the effect of the aperture correction recommended by Helsdon et al. (2000). The thin solid line is the best fit to the observed T-L relation suggested by David et al. (1993). The dotted line shows the median T-L relation from a model in which heat input from galaxy formation is ignored, while the dot-dashed line shows how this model is affected by including cooling (but no heating — see Appendix A). *Lower panel:* as upper panel, but for a model with stronger heating efficiency, $\epsilon_{\rm sn} = 2\,h^{-1/2}$.

probably also required. If the heating associated with galaxy formation is insufficient, the model predictions at the bright end fall too steeply with decreasing luminosity. Even with an efficiency of $\epsilon_{\rm SN} = 1.3h^{-1/2}$, the luminous clusters ($L_{\rm X} > 10^{44}h^{-2}\,{\rm ergs\,s^{-1}}$) tend to lie on an T-L relation which is somewhat too steep. These clusters are little affected by this level of heating and tend to follow the self-similar slope. To bring the most luminous clusters into line with the observed T-L slope, requires that the injected energy be increased to $\epsilon_{\rm SN} = 2.0h^{-1/2}$. However, this model fails to reproduce the presence of X-ray luminous clusters with temperatures below 1 keV (Fig. 2, lower panel). The overall suggestion is that the excess energy should be slightly greater in the progenitor haloes of the most massive clusters. This would be the case if galaxy formation (or AGN activity) were even more strongly biased to high density regions than in the Cole et al. model.

The model results show considerable scatter which arises from two sources. Firstly, haloes collapse over a range of redshifts, leading to some variation in core density. Secondly, the efficiency of galaxy formation varies from halo to halo resulting in considerable scatter in the level of heating. The scatter in the model is in reasonably good agreement with the observational data, although it fails to encompass a small number of clusters with high temperature and low X-ray luminosity. The transient effects of cluster mergers are not included in the present model.

The free parameters of the model have now been fixed to match the present-day relation, and so the evolution to higher redshift provides a test of the model. As discussed in the previous section, the evolution of the T-L relation is determined by a competition between the increasing density of collapsed structures, the temperature distribution of the clusters and the relative importance of the excess energy. The thick dashed line in Fig. 2 shows the median T-L relation at $z = 0.5$. There is little evolution in this relation, consistent with presently available data on distant clusters (Mushotzky & Scharf 1997; Fairley et al. 2000). There is a tendency for clusters of a given temperature to become more X-ray luminous at high redshift, but the trend is too weak to be rejected on the basis of currently available data. Fairley et al. (2000) have analysed the evolution of the T-L relation in a large sample of clusters from $z = 0.2$ to 0.8. They fit their results to a parameterised form, $L \propto T^{3.15}(1+z)^{\eta}$, and derive $\eta = 0.60 \pm 0.38$ for an *open* $\Omega_0 = 0.3$ universe. This corresponds to $\eta = 0.75 \pm 0.48$ in our flat cosmology, since the luminosities inferred from the data are greater. At $T = 5\,{\rm keV}$ our model produces a factor of 1.86 increase in the median cluster luminosity over the redshift interval 0.0 to 0.5, corresponding to $\eta = 1.54$. Thus, the evolution predicted by our model is compatible (at 1.6σ) with that observed by Fairley et al.

3.2 The X-ray Luminosity Function

The heating model provides a good description of the present-day T-L relation, and can account for its observed lack of evolution. We now consider the X-ray luminosity function (XLF). Since the galaxy formation model generates a statistical sample of haloes, the X-ray luminosity function can be readily obtained by appropriate weighting of each

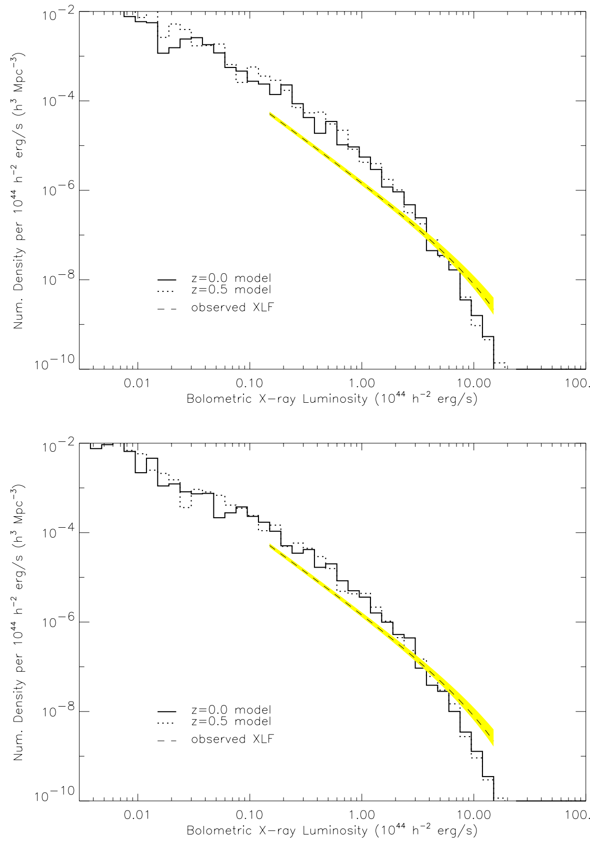

Figure 3. *Upper panel:* the X-ray luminosity function (XLF) at $z = 0$ (solid) and at $z = 0.5$ (dotted) for a heating efficiency $\epsilon_{\rm SN} = 1.3h^{-1/2}$. The dashed line shows the observed present-day luminosity function of Ebeling et al. (1997), with the shaded region illustrating the statistical uncertainty. *Lower panel:* as above, but for $\epsilon_{\rm SN} = 2.0h^{-1/2}$.

halo. The local luminosity function is shown in Fig. 3 (solid line) together with the model predictions at $z = 0.5$ (dotted line). The upper and lower panels correspond to the values of the efficiency parameter, $\epsilon_{\rm SN} = 1.3\,h^{-1/2}$ and $\epsilon_{\rm SN} = 2\,h^{-1/2}$ respectively, introduced to match the observed temperature-luminosity relation. These predictions are compared to the observed local luminosity function derived by Ebeling et al (1997) from the ROSAT all sky "Bright Cluster" survey (BCS). Since the available X-ray data are restricted to relatively bright clusters, we expect a better fit with $\epsilon_{\rm SN} = 2.0\,h^{-1/2}$ than with $\epsilon_{\rm SN} = 1.3\,h^{-1/2}$. This is indeed the case, with the lower $\epsilon_{\rm SN}$ model producing a luminosity function that is too steep. For $\epsilon_{\rm SN} = 2.0\,h^{-1/2}$ the match to observations is better, although there is still a tendency for the model to over-predict the abundance of clusters below the knee of the luminosity function, and to underestimate it at the bright end. The discrepancy can be traced back to the slight bend in the T-L relation seen in Fig. 2, at the temperature at which the effect of the injected energy becomes significant. The fit could be fine-tuned by introducing greater bias in the energy input (eg. if galaxy formation were more prevalent in proto-cluster regions) or by adjusting the cosmological parameters. For example, adopting $\sigma_8 = 0.73$ and $\Gamma = 0.07$ reduces the number of small mass haloes while boosting the abundance of the highest mass objects. This gives a significantly improved match to the luminosity function, but such a small value of Γ may not be compatible with measurements of large-scale galaxy clustering (Peacock & Dodds, 1994, Hoyle et al., 1999, Eisenstein & Zaldarriaga, 2000).

Below the limits currently probed by the BCS luminosity function, the model predicts a significant flattening of the cumulative luminosity function. This is an unavoidable consequence of energy injection: in low mass haloes, most of the gas is ejected resulting in very low luminosities and 'stretching' the luminosity function in this region. The space density of low-luminosity ($L_X < 10^{42}h^{-2}\,\mathrm{ergs\,s^{-1}}$) systems is therefore a strong test of this model. The absence of luminous haloes around spiral galaxies reported by Benson et al. (2000) supports this aspect of the model.

The evolution of the luminosity function is another important test of the model. The dotted line in Fig 3 shows the XLF at $z = 0.5$. This evolves very little relative to the present-day function. The trend arises partly from the weak evolution of the temperature function in this cosmological model (Eke et al. 1998) combined with the trend of increasing luminosities with higher redshift at fixed temperature seen in Fig 2. The model predictions compare very favourably with the available measurements from deep ROSAT surveys (eg. Scharf et al. 1997; Rosati et al. 1998; Vikhlinin et al. 1998; Nichol et al. 1999; Jones et al. 2000) which show no significant evolution of the luminosity function over the redshift base-line 0–0.8. The evolution seen at the bright end is, however, sensitive to the power spectrum adopted. For instance, the $\sigma_8 = 0.73$, $\Gamma = 0.07$ model discussed above suggests that the most massive clusters ($L_X > 5 \times 10^{44}h^{-2}\,\mathrm{ergs\,s^{-1}}$) should have significantly lower space density at $z = 0.5$ than at the present day. It is currently unclear whether this is supported by current X-ray data (see Jones et al. 2000 for a discussion).

3.3 X-ray Emission in the High-Redshift Universe

We can use the model to predict the evolution of the X-ray emission from haloes out to very high redshifts ($z > 2$). The Cole et al. (2000) model of galaxy formation and evolution matches reasonably well observations of the evolution of the universal star formation rate and its dependence on halo mass, over these long look-back times. We can thus trace the evolution of the supernova heating contribution out to very high redshift as required in order to model the evolution of the XLF at extreme redshifts. We focus on the $\epsilon_{\mathrm{SN}} = 2.0\,h^{-1/2}$ model in what follows.

The model prediction is shown in Fig. 4, which compares the T-L relations at $z = 2$ and at the present. At a given temperature, clusters are substantially more luminous than their present-day counterparts. However, because of hierarchical clustering, high temperature systems become increasingly rare at high redshift. At $z = 2$, the decline in abundance offsets the modest increase in X-ray luminosity. This leads to the near constant abundance of clusters at a given X-ray luminosity seen in the lower panel of Fig. 4 and a decreasing contribution of such sources to the X-ray background (as required by Burg et al. 1993 and Wu et al. 1999b).

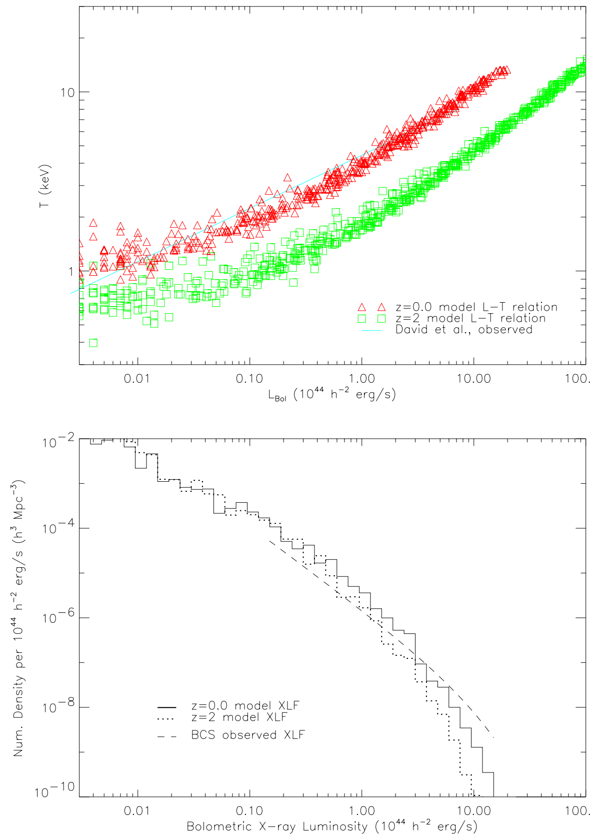

Figure 4. Predictions for the X-ray universe at $z = 2$. *Upper panel:* the T-L relation (triangles: $z = 0$, squares: $z = 2$). *Lower panel:* the X-ray luminosity function (solid: $z = 0$, dotted: $z = 2$). Both panels assume $\epsilon_{\mathrm{SN}} = 2.0\,h^{-1/2}$.

The luminosity function at $z = 2$ is shown in Fig. 4. Even at this large redshift, the luminosity function is predicted to be close to that observed at the present-day.

3.4 The Epoch of Galaxy Formation

We have argued that the slope of the temperature-luminosity relation reflects the energy input from the formation of galaxies and AGN. Now we examine whether the evolution of clusters can be used to constrain the epoch at which this heating occurs. We contrast the GALFORM model (with $\epsilon_{\mathrm{SN}} = 2.0\,h^{-1/2}$) with two simple models. In the first, the heating occurs at a constant rate over cosmic time (model A); in the second the heating occurs at high redshift so that the excess energy remains constant below $z = 2.0$ (model B). Model B is intended to mimic the effect of "pre-heating" the intergalactic medium as in the model proposed by (eg.) Balogh et al. (1999). The total energy injection has been adjusted to match the present-day XLF of the GALFORM model.

We contrast these two simple models with our fiducial model based on hierarchical galaxy formation in Figure 5. The upper panel shows the median T-L relations derived from each of the models at $z = 2$. Similar, but less pronounced differences exist at $z = 1$ and at $z = 0.5$. The models diverge at low luminosities since the relative effect

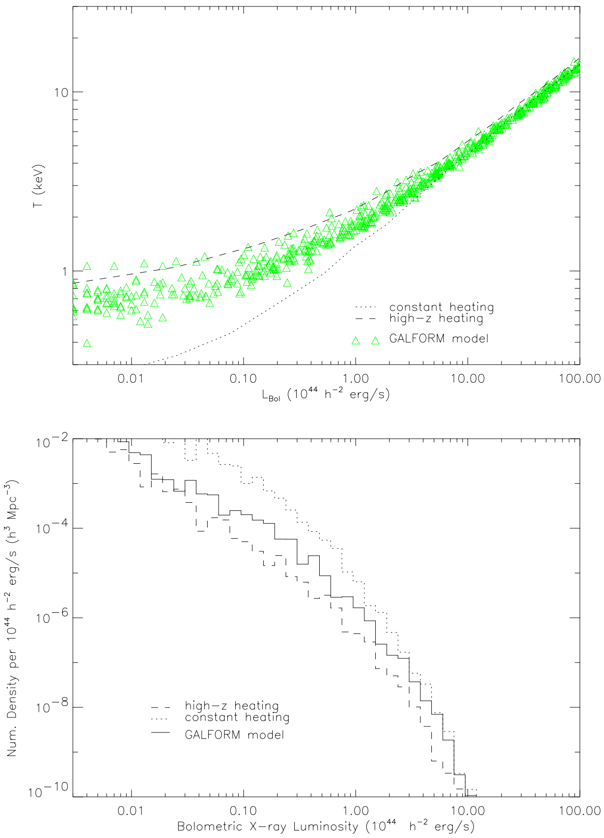

Figure 5. Comparison of different models for the input of the excess energy. *Upper panel*: the temperature function for the GALFORM model compared to (a) a model in which the heating occurs at a uniform rate (dotted line) and (b) a model in which the heating occurs at high redshift (dashed line). *Lower panel*: the X-ray luminosity function for the same models. Both plots show cluster properties at $z = 2$.

of the injected energy is greatest for small clusters. It is not surprising that the differences between the models at the bright end are small. As expected, the two simple models bracket the GALFORM model, although the latter seems closer to model A in which the heating occurs at high redshift. This reflects a bias inherent in clusters. In such dense regions, galaxy formation is accelerated relative to an average region of the universe.

The lower panel in Fig. 5 shows the differences in the luminosity function at $z = 2$ in the three models. As expected from the upper panel, the two models again bracket the behaviour of GALFORM. The luminosity function of the constant heating model shows more positive evolution (ie. a higher number density at higher redshift) than the model in which the heating has already occurred before this epoch. These differences offer an interesting approach to determining the epoch of galaxy formation. If it is possible to distinguish between these heating models by observations, it becomes possible to identify the epoch at which baryons were able to cool efficiently and hence provide a reservoir of cold gas for the formation of stars.

4 DISCUSSION

As we have shown, a model in which the intracluster gas is heated as galaxy formation proceeds provides a good explanation for the slope of the T-L relation and the evolution of the X-ray luminosity function. The problem with associating this energy with galaxy formation is the large amount that is required, between 1.3 and 2.0 $\times\ 10^{49} h^{-1/2}$ erg per solar mass of stars formed. This corresponds to an energy of 0.6 – 1.0 keV per particle in the intracluster medium. This is comparable to the energy injection requirement (1 – 2 keV) derived by Wu et al. (1999a), showing that the overall conclusion does not depend on the details of the implementation of the excess energy principle. Even with optimistic assumptions about the supernova rate, the injected energy would need to couple to the intergalactic plasma with an efficiency close to unity. This seems unrealistic.

An alternative source of excess energy is AGN and/or quasars. If AGN activity is closely linked to the fuelling of star formation, then such activity will enhance the value of $\epsilon_{\rm SN}$. This assumption can therefore be readily incorporated into our model. If, however, the energy input comes predominantly from the most powerful AGN sources early on in the formation history of the universe, it would be more appropriate to treat the energy injection as a uniform preheating of the gas prior to gravitational collapse. If the energy sources were sufficiently uniform, such a model might be better described by the minimum gas entropy model (eg. Evrard & Henry 1991; Navarro, Frenk & White 1995; Bower 1997; Balogh, Babul & Patton 1999; Valageas & Silk 1999). A possible problem of this scheme is the high temperature it implies for the diffuse IGM. For example, Balogh, Babul & Patton (1999) require a temperature of 1.8×10^6 K for a preheating epoch of $z = 3$ in our ΛCDM cosmology. This is in stark contrast to the IGM temperature estimated from the Doppler widths of Ly-α forest lines. For example, Theuns et al (1999) estimate $T_{\rm IGM} \sim 15,000$ K at this redshift. Thus unless the clouds giving rise to the Ly-α forest or the precursor gas of the IGM are atypical, a model in which the heating occurs within already virialised haloes seems preferable.

A limitation of the approach we have adopted is that the excess energy is treated as being independent of the energy released as the clusters and groups merge. Clearly this is only an approximation; it is quite possible that the excess energy affects the way in which the binding energy is distributed between gas and dark matter as mergers proceed. For example, a merger of systems with large energy excess might result in less energy being transfered from the dark matter to the gas compared to a similar merger without excess energy. Such an effect could give rise to an “amplification” of an initial energy excess.

A similar “amplification” effect might be induced by cooling. We have argued that cooling alone cannot explain the slope of the T-L relation because, in the absence of an energy excess, the cooling radius is only weakly dependent on cluster mass and the radiated energy is a greater fraction of the total energy in systems of lower mass. However, once the slope of the T-L relation is sufficiently small to match the observations, cooling becomes relatively more important in the massive clusters, $E_{\rm rad}/W \propto T^{1/2}$ (using the notation of Appendix A). Nevertheless, an estimate of the magnitude of this effect shows that it is not sufficient. Relative to a cluster with $T = 10$ keV, a group at $T = 1$ keV will be a factor 3 less luminous than would be the case if $E_{\rm rad}/W$ were constant. Thus, the small systems gain excess energy at roughly twice their observed luminosity, ie. about $2\times10^{42}h^{-2}\,{\rm ergs\,s^{-1}}$. Over 10^{10} yrs, this will supply an excess energy of $5 \times 10^{59}h^{-2}$ ergs. Since the stellar mass of such a system is approximately $8 \times 10^{11}h^{-1}M_{\odot}$, the net gain in excess energy is equivalent to a supernova heating rate of $\epsilon_{\rm SN} = 0.06h^{-1}$ which is too small to affect the gas distribution in these systems significantly. However, it is clearly vital to understand both of these processes better, for example through well targeted numerical simulations (eg. Pearce et al. 2000).

Finally, we must recall that galaxy formation and X-ray evolution have not been treated in a fully self-consistent fashion in this paper. We have taken the successful GALFORM model of galaxy formation, and used it to predict the evolution of cluster and group X-ray properties. In practice, we should use the methods developed here to calculate the gas density profile of all haloes at each epoch, compute gas cooling rates using these profiles and then calculate the excess energy from the current star formation. This represents a huge computational overhead on the standard GALFORM model, but is clearly an important next step to take.

5 CONCLUSIONS

In this paper, we have addressed the problem of why the observed properties of X-ray clusters do not conform to simple scaling relations. In particular, we have considered why the observed correlation between X-ray temperature and X-ray luminosity is significantly shallower than the scaling solution, while the X-ray luminosity function evolves less rapidly than predicted in popular cold dark matter cosmologies. First, we argued that the effects of gas cooling in clusters (which break the scaling relations) do not resolve the problem. We then considered the heating of the intracluster gas by the energy released during galaxy formation by combining the semi-analytic model of Cole et al. (2000) with a simple model for the thermodynamic state of the intracluster gas. Our main conclusions, applicable in the ΛCDM cosmology may be summarized as follows:

- Heat input into the intracluster gas by processes associated with the formation of cluster galaxies, such as supernovae and/or AGN winds, flatten the slope of the temperature-luminosity relation. The combined model gives a reasonable match to observations if energy is injected at a level of 1.3–2.0 $h^{-1/2}$ ergs per solar mass (or, equivalently, 0.6–1 keV per particle in the intracluster medium). Values within this range produce broadly acceptable models, but lower values result in a better match to groups with $T \approx 1\,{\rm keV}$, while higher values produce a better match to the most massive clusters.
- The interplay between the energy injection rate during galaxy formation and the rate at which clusters grow by hierarchical clustering causes the $T - L$ relation to evolve little with redshift. This is consistent with recent data based on ASCA observations.
- The $z = 0$ X-ray luminosity function in the model approximately matches observations, but the model over-produces low mass groups and under-produces very massive clusters. Fine tuning the cosmological parameters or other details of the model may remove these discrepancies.
- Similar factors to those that regulate the evolution of the $T - L$ relation result in only weak evolution of the luminosity function to $z = 0.5$. This too is consistent with current data.
- The properties of clusters at high redshift provide a test of the model since all free parameters are fixed to achieve agreement with present-day data. In particular, the model predicts little evolution in the X-ray luminosity function even out to $z = 2$. The predicted near constancy of the luminosity function is, in principle, testable, but it is unlikely that the detailed structure of collapsing proto-clusters will be observable with the current generation of X-ray satellites.
- The main difficulty of our model is that it requires an amount of energy per mass of stars formed which is comparable to the total energy available from supernovae. This would need to couple to the intracluster gas with very high efficiency. However, additional energy sources associated with galaxy formation may also contribute, such as the mechanical energy liberated by AGN winds. Alternatively (or additionally), an initial heat input might be amplified by the response of the intracluster medium to protocluster mergers. Detailed numerical simulations are required to quantify this process.

Our work demonstrates that the shape and evolution of the X-ray luminosity function and T-L relations are potentially powerful probes of the mode and efficiency of galaxy formation. Future observations with Newton and Chandra should be able to test these ideas.

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APPENDIX A1: THE EFFECT OF COOLING ON THE T-L RELATION

Dimensional analysis offers a powerful insight into the evolution of clusters (eg. Kaiser 1986, 1991; Evrard & Henry 1991; Bower 1997; Kay & Bower 1999). This approach can be used to show that the bolometric X-ray luminosity of clusters should obey a scaling law:

$$L_{\rm X} \propto T^2 (1+z_{\rm f})^{3/2}. \qquad \text{(A1)}$$

This relation assumes that the volume emissivity of the gas scales as $\rho^2\Lambda(T)$, where $\Lambda(T) \sim T^{1/2}$ is the cooling function, $\rho \propto M/R^3$ is the gas density, and T is the gas temperature. (M and R are the characteristic cluster mass and radius, respectively.) We have explicitly included the dependence on the collapse redshift of the cluster, $z_{\rm f}$, to make it clear that the scaling depends on this rather than on the redshift at which the cluster is observed.

As we have discussed, the T-L relation implied by eqn. (A1) is too steep compared with the observed luminosities and temperatures of clusters. Eqn. (A1) suggests that the relation might be made shallower if lower temperature clusters had systematically lower collapse redshifts. In hierarchical models, however, smaller mass clusters are expected to collapse at higher redshifts — the opposite to the required trend.

Cooling introduces an additional scale into the problem, which is absent in the above analysis. There are two competing effects introduced by cooling. Firstly, systems which radiate a large fraction of their energy become more tightly bound (they develop a negative excess energy in the language of §2) and thus move to higher X-ray luminosities. Secondly, mass may cool out of the intracluster medium so that it is no longer visible at X-ray wavelengths. Depending on how the remaining gas reacts, the loss of this material may reduce the overall density of the gas that remains, thus lowering the X-ray luminosity. These two effects work in opposite directions, and will tend to compensate for each other. We consider them separately below in order to investigate the maximum effect that cooling can have.

We firstly consider the energy balance argument. If cooling is more important in higher (lower) temperature systems, it might reduce (increase) the slope of the T-L relation compared to the scaling analysis solution. The relative importance of cooling can be assessed by comparing the energy radiated by the cluster over its lifetime ($E_{\rm rad}$) with the cluster's total energy ($W \propto -M^2/R$). Since the cluster is in virial equilibrium, the total energy can be expressed in terms of the gas temperature so that

$$\frac{E_{\rm rad}}{W} \propto \frac{L_{\rm X} t_{\rm H}}{MT} \propto T^{-1/2}(1+z_{\rm f})^3 t_{\rm H}. \qquad \text{(A2)}$$

We have used the Hubble time, $t_{\rm H}$, in this expression rather than the shorter lifetime of the halo in order to gauge the maximum effect that cooling can have. Eqn. (A2) shows that *lower* temperature clusters radiate a larger fraction of their total energy. The effect of cooling is therefore to *steepen* the T-L relation, exacerbating the discrepancy with the observed relation.

There is still a loophole in this analysis, however, since we have assumed that all the cooling gas continues to emit at X-ray wavelengths. The second possibility is that the cooling rapidly depletes gas at the centre of the cluster, creating a core in the gas density distribution. This mechanism seems encouraging since lower temperature systems will develop larger cores relative to their virial radii. We associate this core radius with the 'cooling radius', the radius at which the cooling time, $t_{\rm cool}$, is equal to the age of the universe, $t_{\rm H}$. (Again we choose the age of the universe rather than that of the halo in order to derive the maximum effect.) This leads to:

$$t_{\rm cool}(r_{\rm cool}) \propto \rho(r_{\rm cool})^{-1} T(r_{\rm cool})/\Lambda(T) \propto t_{\rm H}. \qquad \text{(A3)}$$

Outside the cooling radius, we assume that cooling can be neglected in this extreme model, and that the density profile, $\rho(r) \sim (1+z_{\rm f})^3 (r/R)^{-2}$.

First, we consider the fraction of gas that is able to cool, $f_{\rm cool}$. Integrating the density profile, shows that $f_{\rm cool} = r_{\rm cool}/R$. Since the X-ray luminosity is dominated by the densest gas,

$$L_{\rm X} \propto r_{\rm cool}^3 \rho(r_{\rm cool})^2 \Lambda(T) \propto \frac{T^2(1+z_{\rm f})^{3/2}}{f_{\rm cool}}. \qquad \text{(A4)}$$

The greater the fraction of gas that is able to cool, the more the luminosity is reduced below that of eqn. (A1). If the cooled fraction increases monotonically as the universe ages, this relation cannot help resolve the discrepancy between the predicted and observed evolution of X-ray luminosity. However, the fraction of gas that is able to cool is actually higher at high redshift than at the present. (This is commonly referred to as the 'cooling catastrophe'.) Thus, if the cooling gas is re-heated rather than locked up in stars or baryonic dark matter, it is possible that subsequent generations of clusters might actually have smaller values of $f_{\rm cool}$ than their high redshift predecessors.

We proceed by assuming that $f_{\rm cool}$ may be calculated independently of the cluster's previous history. Using the definition of the cooling radius, we find,

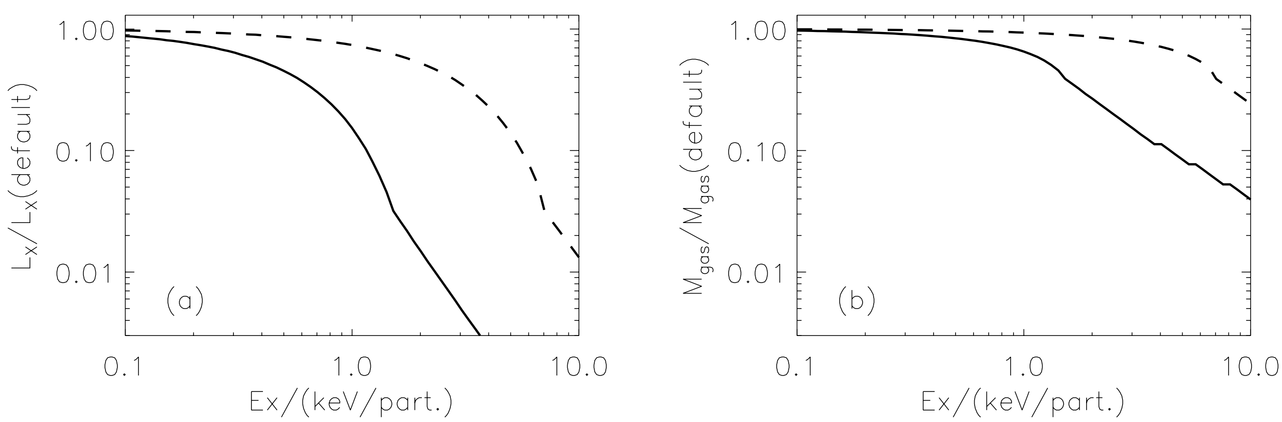
$$\frac{r_{\rm cool}}{R} \propto \left(t_{\rm H}\rho_0 T^{-1/2}\right)^{1/2}. \qquad \text{(A5)}$$

Applying this to calculate the scaling of the X-ray luminosity gives:

$$L_{\rm X} \propto T^2 \Lambda(T)^{1/2} t_H^{-1/2} \propto T^{9/4} t_{\rm H}^{-1/2}. \qquad \text{(A6)}$$

This only slightly improves the match to the data. For high temperature clusters, the relation becomes slightly shallower, but the effect is not sufficient. Moreover, in cooler clusters, the emissivity is enhanced by recombination radiation and the slope of the T-L relation becomes steeper again.

A numerical implementation of this scenario is illustrated by the dot-dashed line in Figure 2. Starting from the default halo profile, we have calculated the fraction of the gas mass within the cooling radius of each of the simulated haloes. The beta profile has then been adjusted so that the remaining gas mass is distributed within the virial radius using the boundary condition discussed in §2. In systems with a large cooling radius, the gas mass is reduced and a lower value of beta is required to give a correctly normalised profile. The T-L relation that results is close to that predicted by the scaling arguments discussed above, and fails to match the observed data. Moreover, it should be remembered that this model represents an extreme scenario, where the energetics of the new gas distribution have not been considered and the cooling has been assumed to occur at a constant rate over the Hubble time.



1.00
0.10
0.01
L_X/L_X(default)
(a)
0.1
1.0
10.0
Ex/(keV/part.)
1.00
0.10
0.01
M_{gas}/M_{gas}(default)
(b)
0.1
1.0
10.0
Ex/(keV/part.)